

Subaqueous Cap Design: Selection of Bioturbation Profiles, Depths, and Process Rates

PURPOSE: When dredged material has been determined to contain contaminants that open-water placement would potentially cause to degrade the benthic environment, subaqueous capping with a layer of clean material may provide an acceptable management alternative. Subaqueous capping of in situ contaminated sediments also represents a potentially effective remediation option. For either practice to satisfy the requirement of isolation of the contaminated sediments, design of caps of clean material must account for multiple factors affecting the long-term stability of the cap. The purpose of this technical note is to present guidance on one of these factors, bioturbation, which consists of various processes whereby organisms modify sediment properties or move sediment particles or solutes within the sediment matrix. Specifically, this technical note focuses on estimation of bioturbation profiles, depths, and process rates in relation to subaqueous cap design.

BACKGROUND: Detailed guidance on engineering considerations for dredged material capping and in situ sediment capping can be found in Palermo et al. (1998a, 1998b). These guidance documents, however, treat the topic of bioturbation only superficially in the context of cap design. This technical note examines bioturbation in greater detail and makes specific recommendations regarding cap designs that will accommodate bioturbation processes while maintaining long-term sediment isolation functions.

Subaqueous caps can be designed to serve three primary functions: (1) physical isolation of contaminated sediments from the benthic environment, (2) stabilization of contaminated material to prevent resuspension and transport to other sites, and (3) reduction of the flux of dissolved contaminants into the water column. In the majority of cases, the primary concern is providing a cap of sufficient thickness to achieve these intended functions. In certain scenarios where remediation is the project goal, placement of a "thin" cap may be considered. In this context the clean cap sediments are allowed to mix over time with the underlying contaminated sediments. This approach to remediation, sometimes referred to as "enhanced natural recovery," is based on the concept that exposures to contaminants would be proportionally reduced while natural attenuation processes would be accelerated.

In addition to cap thickness, an important consideration in cap design is the selection of material of appropriate geotechnical properties, mainly grain size distribution, that optimizes the long-term stability requirements of the cap. Grain size distribution has important implications in determining the types of biota that will occupy the surficial sediments and ultimately bioturbation effects on cap integrity. Typically, subaqueous caps consist initially of a homogeneous layer of granular material. Sand caps, for example, can be expected to behave differently from caps composed of silts or clays, as different assemblages of bioturbating organisms have affinities for different sediment types.

Determination of required cap thickness must include consideration of the potential for bioturbation within the cap as well as physical and chemical properties of the contaminated and capping

sediments, potential consolidation of the contaminated sediments and resultant expulsion of pore water, consolidation and erosion of the cap material, groundwater flow gradients, and operational factors (e.g., engineering constraints on the mode of cap placement). Total cap design thickness therefore represents an integration of various components that accommodates these multiple interacting processes. Current guidance defines total cap thickness as the sum of these contributing components, which exceeds that required for bioturbation alone.

Appropriate consideration of bioturbation is essential to formulation of an effective cap design. Bioturbation is a broadly defined term that includes a number of distinct processes, including bioadvection, biodiffusion, and bioirrigation, that influence sediment properties. Hence, obtaining a basic understanding of how biota could affect cap functions at a given site should be recognized as an important step in the planning of capping projects.

DEFINITIONS: Given these considerations, the following definitions are applicable to the content of this technical note:

- **Bioadvection** – nonrandom, generally vertical fluxes of particles due to biological activity such as feeding and burrow construction or maintenance.
- **Biodiffusion** – transport of materials, including contaminants, through the sediment column both vertically and horizontally as a result of biological activity.
- **Bioirrigation** – movement of water and solutes within and out of the sediment column due to active or passive flushing of infaunal burrows.
- **Bioturbation** – the movement or alteration of sediment particles or pore water mediated by organisms.
- **Cap design parameters** – the composition and dimensions of materials composing a sediment layer that achieves effective isolation of contaminated sediments.
- **Clean** – sediments determined to be acceptable for use as capping material, i.e., suitable or acceptable for open-water placement.
- **Contaminated** – sediments for which isolation from the benthic environment is appropriate because of potential detrimental effects.
- **Contaminant flux** – movement of contaminants within sediment layers or through the sediment/water interface via advection with pore water or molecular diffusion.
- **Subaqueous capping** – the controlled, accurate placement of contaminated dredged material at an appropriately selected open-water site, followed by placement of a covering layer or “cap” of clean material; the placement of clean material over an existing in situ deposit of contaminated sediments.

BIOTURBATION PROCESSES RELEVANT TO CAP DESIGN: An extensive and growing body of scientific literature supports the basic finding that bioturbation has significant effects on sediment properties in almost all aquatic environments. Although several literature reviews exist (e.g., Lee and Swartz 1980; McCall and Tevesz 1982; Krantzberg 1985; Matisoff 1995), none has focused on the implications of bioturbation for the construction and performance of sediment caps.

An extensive review of the literature is beyond the scope of this technical note, but a condensed synthesis of the pertinent literature is made, with an emphasis on citation of more recent references. An updated bibliography on the topic of bioturbation will be published at a later date. Similarly, an extensive scientific literature exists on the mechanisms by which benthic organisms affect transport and uptake pathways of specific contaminants. Herein discussion of this topic is limited to the roles of bioturbation processes such as burrow construction and maintenance and bioirrigation of sediments during feeding and respiration. This topic is examined in greater detail by Officer and Lynch (1989); Reynoldson (1987); Reidel, Sanders, and Osman (1989); Soster et al. (1992); and Davis (1993).

The intensity and depth to which bioturbation occurs in the sediment column are highly site specific, reflecting the myriad behaviors of diverse assemblages of benthic organisms and their interactions with the physical environment (Schaffner et al. 1987; Wheatcroft, Olmez, and Pink 1994). The composition of benthic assemblages is in turn influenced by substrate characteristics, including grain size distribution, compaction, organic content, and pore-water geochemistry. Although the processes involved are similar, shifts in taxonomic composition of bioturbators occur as one moves from coastal marine through estuarine to freshwater environments. Although essentially absent in marine systems, insects such as the mayfly *Hexagenia* are often dominant bioturbators in lacustrine habitats (Svensson and Leonardson 1996; Charbonneau and Hare 1998; Matisoff and Wang 1998). Oligochaetes (Soster et al. 1992; Van Rees, Reddy, and Rao 1996) and amphipods (Krezoski, Mozley, and Robbins 1978) are also important freshwater bioturbators. Diverse assemblages of polychaetes, crustaceans, and bivalve mollusks play similar roles in marine systems (Rhoads 1974). An assessment of the maximum or predominant depth of bioturbation-induced sediment mixing at any given site must be based on knowledge of the biological assemblage at that particular location.

The concept of capping contaminated sediments with clean sediments has existed for several decades, and among the first environmental concerns raised was that of potential bioturbation effects on cap effectiveness. Much of the early work to address this issue was conducted in conjunction with capping projects in the northeastern United States. A series of laboratory investigations demonstrated the need to add a "safety margin" to the cap thickness required to achieve chemical isolation (Brannon et al. 1985, 1986; Gunnison et al. 1987). Brannon et al. (1985) reported that the burrowing polychaete *Nereis virens* penetrated 50-cm-thick experimental caps of either sand, silt, or clay.

Rhoads and Carey (1997) evaluated the role of bioturbation in the context of cap design in estuarine and coastal settings. They reported that colonization of benthic organisms can have pronounced effects on the characteristics of surficial sediments of subaqueous caps of dredged material mounds. The types and magnitudes of effects are dynamic through time following colonization as the composition of organisms changes. For example, sediment particle binding by dense communities of small, tube-building worms and crustaceans can have an overall stabilizing effect, particularly during the early stages (1-2 years) of colonization (Figure 1). These tube-dwellers also pump water into and out of their tubes, thereby causing oxidation of sediments surrounding the base of the tubes to a depth of approximately 3 cm. During ensuing stages of colonization (2-5 years), tube-dwellers are gradually replaced by deeper burrowing organisms (Figures 2 and 3). This transition alters the dominant mode of bioturbation from near-surface binding to deeper (approximately 10 cm) mixing. Burrowing generally results in increased sediment water content, decreased sediment cohesion, and

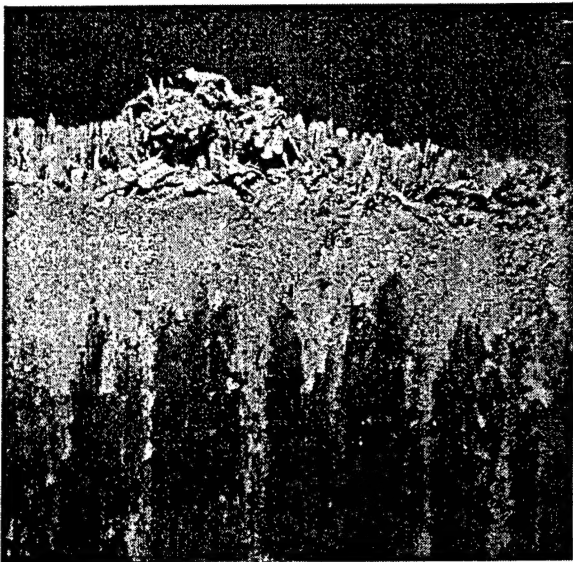


Figure 1. Cross section of the sediment/water interface (approximately 15 by 15 cm), showing a dense assemblage of amphipod tubes at the surface

Figure 2. Polychaetes below the sediment/water interface in an estuarine environment

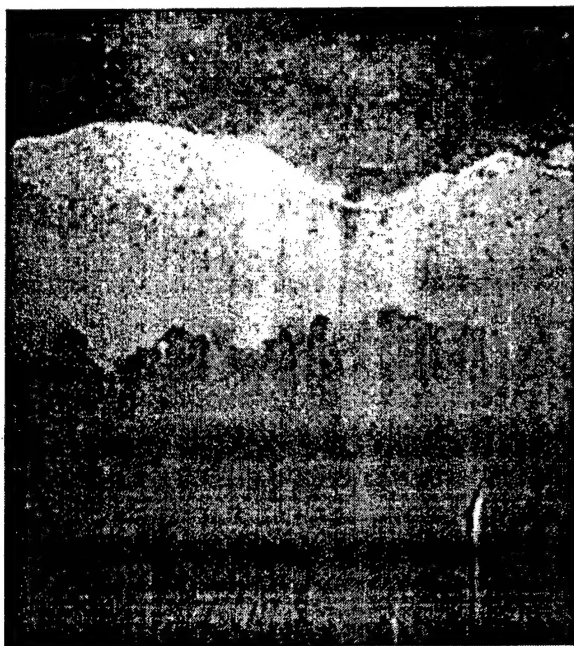


Figure 3. Well-mixed, oxic sediments overlay reduced sediments in a freshwater habitat. An oligochaete can be seen at a depth of about 10 cm

increased pore-water exchange. Late stages of colonization are often dominated by less dense assemblages of large organisms, many of which feed in a head-down position at sediment depths approaching 30 cm (Figure 4). These "conveyor-belt" feeders ingest sediment at depth and defecate at the surface, thereby moving appreciable volumes of sediment. This very concise summary of benthic community succession captures very general trends, as described in Pearson and Rosenberg (1978), Rhoads and Boyer (1982), and Rhoads and Germano (1987); but the actual sequence observed in the field can vary greatly. Also, this description pertains largely to colonization of unconsolidated sediments, whereas succession in sandy sediments, although likely to follow similar patterns, is less well understood.



Figure 4. A large feeding void, created by head-down deposit feeding polychaetes

The Rhoads and Carey (1997) review specifically addressed bioturbation issues relevant to caps in coastal environments. The significance of bioturbation processes in freshwater ecosystems is also well-established (McCall and Tevesz 1982). Several aspects of bioturbation in both saltwater and freshwater environments are acknowledged to be important gaps in the pertinent state of knowledge. First, while the role of infauna (i.e., organisms dwelling in intimate association with the sediment matrix) within the uppermost 30 to 50 cm of the sediment column is relatively well studied, the role of deep-burrowing (>50 cm) invertebrates remains unquantified. For example, echiuran worms are known to build large burrows to a depth of up to 80 cm in muddy sediments (Hughes, Atkinson, and Ansell 1999).

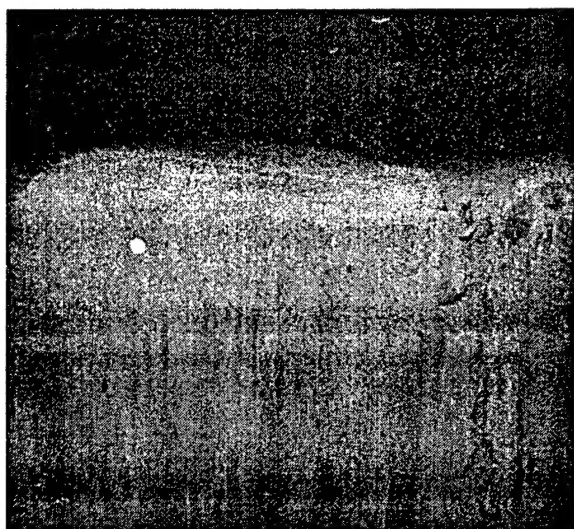


Figure 5. A large vertical burrow, possibly constructed by a mantid shrimp, extends downward through the sediment column

Certain species of crustaceans, notably mud shrimp (families *Thalassinidae* and *Callinassidae*) and mantid shrimp (family *Squilla*), have been documented to construct burrow galleries below a depth of 1 m (Pemberton, Risk, and Buckley 1976; Myers 1979; Swift 1993) (Figure 5). Likewise, the role of "megafauna," primarily large invertebrates and fishes, is generally unknown but may be locally significant (Atkinson and Taylor 1991). An example of the latter would be foraging pits excavated by large skates and rays (Howard, Mayou, and Heard 1977).

Although the role of meiofauna (i.e., benthic organisms <0.25 mm in size, including nematodes and juvenile stages of polychaetes) as bioturbators has received little attention, the few documented studies indicate that their effects on solute transport and other processes are small in comparison with

macrofauna and are generally confined to superficial oxidized sediments (Aller and Aller 1992). Their consideration in general cap design is therefore noncritical.

As implied in the discussion of benthic community succession, the effects of bioturbation on sediment stability are relatively well known. In brief, both microbial and infaunal activity can increase the shear strength of surficial sediments. Mucopolysaccharide secretions of diatoms (Sutherland, Amos, and Grant 1998) or tube and burrow wall binding secretions of amphipods and polychaetes (Meadows, Tait, and Hussain 1990) typically have a sediment stabilizing effect. However, the scale of bioturbation-induced alteration of shear strength may be minor in comparison with periodic, physically driven hydrodynamic forces acting on sediment caps in shallow waters.

BIOTURBATION PROFILES: An understanding of the vertical distribution of bioturbation activity is helpful for effective cap design. In almost all benthic communities, biological activity is most intense in the uppermost portion of the sediment column and decreases with depth (e.g., Hines and Comtois 1985; Gerino 1990). In spite of differences in taxonomic composition of benthos, there appears to be a high level of correspondence between marine and freshwater benthic communities in terms of distribution and intensities of bioturbation processes (McCall and Tevesz 1982; Rhoads and Boyer 1982). Given this generalization, bioturbation can be conceptually partitioned into three zones (Figure 6). An upper layer contiguous to the sediment/ water interface will be subject to frequent and thorough mixing by shallow bioturbating organisms. This surficial zone, usually associated with the redox potential discontinuity, or boundary between oxic and anoxic sediments, extends to a depth of 10 or more centimeters. Depending on site characteristics, a second, middepth zone represents the presence of larger but usually less dense bioturbators, which occur during later stages of colonization. For example, a number of bivalve mollusks inhabit this zone, their burial depth a function of body size and siphon length (Zwarts and Wanink 1989).

Actual intensities of bioturbation processes vary temporally with depth reflecting seasonal components of benthic population dynamics. For example, Wheatcroft, Olmez, and Pink (1994) found quite different profiles of particle bioturbation in spring versus fall samples at a site 32 m deep in Massachusetts Bay. They speculated that shifts in dominant modes of bioturbation likely accounted for these observed differences. Notwithstanding evidence for small spatial and temporal scale variation in bioturbation at a site, a general pattern of decreasing activity of benthic organisms with increasing depth down to 10-40 cm appears to be consistent across aquatic habitats. Thus the predominant bioturbation processes are likely to be surficial mixing and middepth biodiffusion. As alluded to previously, a third zone represents the possible presence of very deep bioturbators. Because there are few data on the distributions of such organisms, an assumption is necessarily made in formulation of cap design guidance that deep bioturbators are not present in significant numbers. In the future, guidance will be revised to accommodate any new evidence that sheds light on the importance of these organisms.

BIOTURBATION DEPTH ESTIMATES: Cap thickness should ideally compensate for bioturbation depths based on known behaviors and depth distributions of organisms that will recruit to cap materials at a given site. In the majority of cases, dominant infaunal organisms and their affinities for sediments of certain characteristics are sufficiently well known to predict their short- and long-term interactions with a cap. However, due to the site-specific nature of factors (e.g., depth, salinity, hydrodynamics, substrate characteristics) that determine the structure of benthic

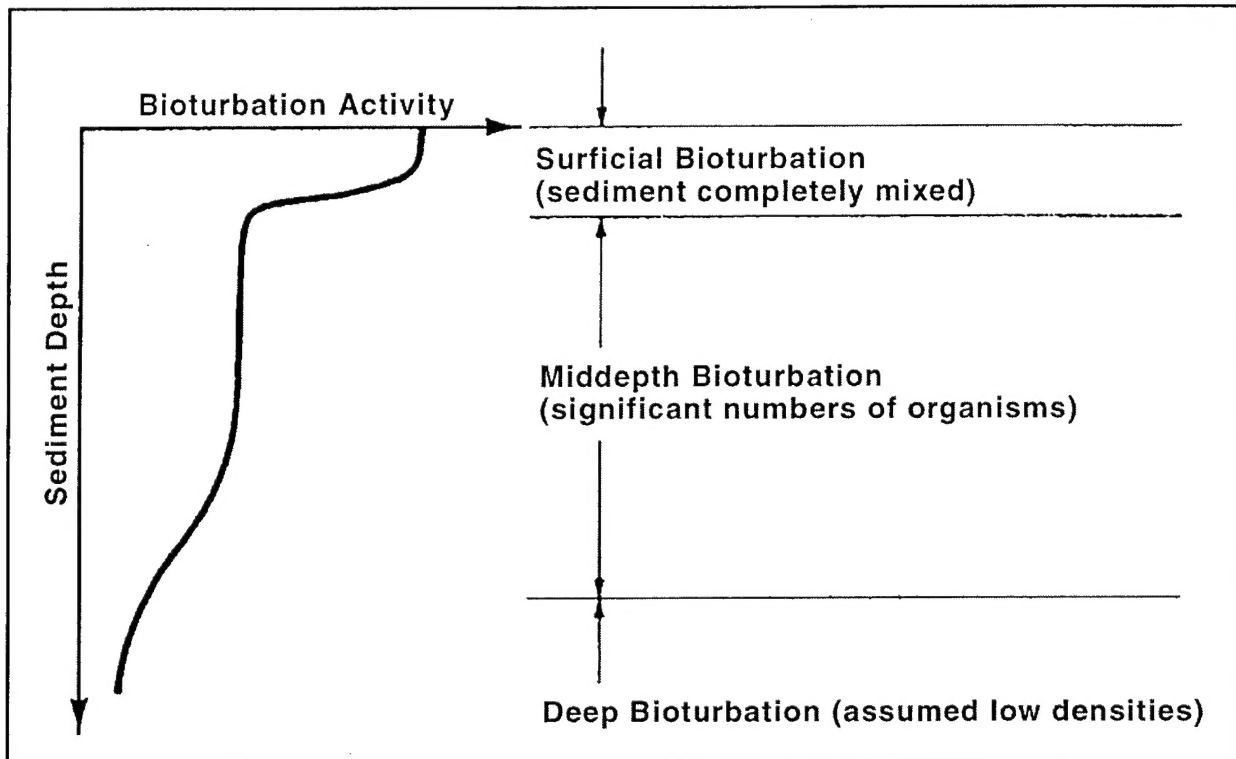


Figure 6. Illustration of the concept of bioturbation "zones" that correspond to intensities and vertical distribution of dominant processes. An upper surficial zone, in which high densities of infaunal organisms completely rework the sediment matrix, overlies a middepth zone, in which infaunal densities are lower and rates of sediment reworking decrease with depth. A deep bioturbation zone, in which the presence of bioturbators may be unknown, extends below the observed limit of middepth bioturbation.

communities, it is highly advisable to obtain the opinions of experts in benthic ecology in the project region. The value of this step has been demonstrated in previous determinations of cap designs in the New York Bight (Rhoads and Carey 1997) and Palos Verdes shelf, California (Palermo et al. 1999) regions. A logical approach to estimating adequate cap thickness therefore incorporates best available information on the probable maximum depth of the middepth bioturbation zone with an incremental buffer to further isolate underlying contaminated sediments from the influence of bioturbation.

In the case of cap evaluation in the New York Bight, Rhoads and Carey (1997) suggested that a cap thickness of 30 cm would adequately isolate underlying sediments from exposure to bioturbation. They based their recommendation on a broad overview of regional macrofauna, which led them to conclude that the biological mixing zone would have a mean depth of 10 cm. The additional 20 cm of cap material would in theory be sufficient to provide long-term isolation from contaminated pore-water advection.

"Fully mixed zones" measured by Swift et al. (1996) at four stations on the Palos Verdes shelf ranged from under 5 cm to almost 30 cm. Based on this information Palermo et al. (1999) recommended that a 30-cm cap component to accommodate bioturbation processes be included in

a cap designed to isolate in situ contaminated sediments there. Additional considerations, including a concern for potential deep bioturbation, led to a 45-cm-thick cap for total isolation.

In situations where site characterization data are poor or expert opinions are unavailable, general observations on bioturbation based on existing scientific literature can be used for initial project planning, preliminary design, and costing purposes. Table 1 summarizes generic estimates of surficial mixing and middepth biodiffusion depths and recommends minimum total bioturbation component thicknesses for caps in a range of environmental settings. Boudreau (1994, 1998) examined the measured mixing depths from a large number of bioturbation studies and calculated a mean depth of 9.8 cm (SD = 4.5 cm). This supports the use of 10 cm as generic guidance for mixing depths in Table 1. Note that a somewhat more conservative value of 15 cm is given for marine silts and clays, where the literature suggests that slightly deeper mixing may occur. The values presented in Table 1 should be used conservatively, and adjusted to take advantage of site-specific information in conjunction with expert opinions whenever possible.

Inclusion of an additional cap thickness increment to compensate for the possible presence of deep

Table 1
A Summary of Recommended Cap Thicknesses for the Bioturbation Component of Cap Design

Environment	Cap Material	Depth of Surficial Zone of Sediment Mixing, cm	Depth Increment for Middepth Zone of Biodiffusion, cm	Total Bioturbation Component Cap Thickness, cm
Coastal/marine	Sands	10	10-35	20-45
	Silts/clays	10-15	10-45	20-60
Fresh water	Sands	10	10-20	20-30
	Silts/clays	10	10-30	20-40

Note: In the coastal/marine sand cap example, 10 cm would accommodate the intensively mixed surficial layer and an additional 10 to 35 cm would be needed to accommodate middepth bioturbation, yielding a total cap thickness of 20 to 45 cm to adequately address overall bioturbation. Values at the lower range of total bioturbation component thickness would be justified only where sufficient knowledge of local benthos supported selection of a shallower depth.

bioturbators may be problematic in achieving a balance between conservative cap design and reasonable construction costs. Because other considerations in cap design (e.g., thickness to offset predicted consolidation and erosion, ability of the placement technique to construct a uniform cap in accordance with specifications) will in many cases result in a design thickness in excess of that required to accommodate surficial and middepth bioturbation, the risk of deep bioturbators affecting cap integrity should be minimal. In rare cases where the presence of moderate to high densities of deep bioturbators is established, extra precautions may be necessary in achieving an effective cap. For example, in the course of a sediment remediation project at Convair Lagoon, San Diego, California, it was determined that several resident species of deep-burrowing shrimps (*Callinassa californiensis*, *Upogebia pugettensis*, and *Alpheus californiensis*) would compromise sand caps less than 1 m thick (Ogden Environmental and Energy Services 1994). One recommendation for cap

design incorporated a 20-cm layer of gravel to be placed below the sand cap to prevent penetration by shrimp burrows.

CONSIDERATIONS FOR EVALUATION OF CAP DESIGN EFFECTIVENESS: If the primary cap design function is to provide chemical isolation, then an evaluation of the short- and long-term flux of contaminants through the cap is required. At present, evaluations of cap effectiveness must be based on laboratory and modeling investigations (Palermo et al. 1998a, 1998b).

Investigations of various aspects of bioturbation have led to mathematical descriptions of individual or multiple processes, or attempts to quantify derived rates and coefficients. It is beyond the scope of this note to relate these studies in detail, but the reader should be aware that such a literature exists. Many of the theoretical results of these studies were based on bioturbation processes in intertidal or deep-sea sediments, which lie outside the realm of most capping scenarios, but the findings should be relevant nonetheless. Examples include, but are not limited to, Matisoff (1982); Boudreau (1998); Wheatcroft et al. (1990); Meadows and Meadows (1991); Boudreau and Marinelli (1994); Gerino, Stora, and Durbec (1994); Mohanty et al. (1998); Smith and Schafer (1999); and Meile, Koretsky, and Cappellan (2001).

Several models are available that can predict long-term movement of contaminants into or through caps via advection or diffusion processes (Thoma et al. 1993; Ruiz, Schroeder, and Aziz 2000). For example, the RECOVERY model (Ruiz, Schroeder, and Aziz 2000) simulates both advective and diffusive fluxes, multiple layers of specified thicknesses, vertical variation in physical properties of the sediments, and vertical variation in concentrations of contaminants in the sediments. Realistic bioturbation depths must be estimated in applications of models such as RECOVERY for prediction of contaminant fluxes. Time scales are an important consideration in model applications. For example, simulations of various cap designs are typically run on time scales of hundreds to thousands of years, whereas bioturbation processes occur on much shorter time scales.

BIOTURBATION RATES: In order for model applications to accurately reflect spatial and temporal scales of bioturbation-related processes, appropriate selection of process rates must be made. With respect to sediment reworking or mixing in the surficial zone, selection of a mixing rate is relatively straightforward, since in most situations this layer can be considered entirely mixed on a very short time scale. If required, estimates of sediment mixing rates for a large number of benthic taxa exist (e.g., Lee and Swartz 1980). However, considering the generalized description of bioturbation given previously, the surficial zone of sediment mixing can be assumed for modeling purposes to be a totally mixed layer that offers no resistance to long-term contaminant flux. Based on a review of the literature on regional benthic assemblages, observations of actual vertical distributions of infauna in local sediment cores, and measured vertical profiles of radionuclide tracers, Wheatcroft and Martin (1994) recommended that 50 cm²/year be used as the upper range estimate for biodiffusivity in the upper 10 cm of Palos Verdes shelf sediments. They also refer to other studies of shelf environments where mixing rates were measured within the 1- to 140-cm²/year range.

The underlying middepth bioturbation zone, where organisms move sediments at slower rates than near-surface organisms, poses a more complex decision in rate selection. Contaminants will be

subject to rates of bioturbation-induced flux that exceed rates due to molecular diffusion alone. As noted by Wheatcroft et al. (1990), bioturbation is typically treated as a vertically diffusive process. Based on an assumption that bioturbation is analogous to eddy diffusion, "bioturbation coefficients" or biodiffusivities D_b were estimated by Guinasso and Schink (1975) by fitting regression lines to observed vertical profiles of tracers in sediment cores. All of the biological processes affecting sediment parameters were thereby reduced to a single measure. Wheatcroft et al. (1990) argued that such a simplistic one-dimensional representation of bioturbation can be misleading. They proposed a modeling protocol that incorporates advective as well as diffusive types of mixing. By including estimates of step length (the square of the distance particles are moved), rest period (elapsed time between movements), and direction of particle movement, they attempted to address the spatial and temporal variability of specific bioturbation processes. For the Palos Verdes study, Wheatcroft and Martin (1994) recommended that biodiffusivity be treated as an exponentially decreasing function below a depth of 10 cm.

Acknowledging that specific rates would be exceedingly difficult to quantify, Wheatcroft and Martin (1994) nevertheless noted that where deep bioturbators are present, advection would likely be of equal or significantly greater magnitude than diffusion. Deep mixing would therefore need to be modeled with an advective component. In systems subject to advection, flux rates within the middepth zone should be modeled as the greater of the two processes, biodiffusion or advection. These recommendations are given with the caveat that a number of factors that influence bioturbation processes, particularly in shallow-water environments, remain poorly understood (Wheatcroft and Martin 1996).

CONCLUSIONS: The following conclusions are made regarding bioturbation with reference to cap design:

- Bioturbation processes as factors influencing cap effectiveness cannot be ignored.
- Based on extensive documentation of vertical profiles of biological activity, three distinct bioturbation zones can be identified. A surficial zone is intensively reworked on relatively short time scales and should be treated as a continually mixed layer for purposes of cap design. A middepth zone is characterized by decreasing activity with increasing depth. A deep zone is poorly understood in comparison with the overlying zones. Here the distributions and abundances of bioturbators are largely unknown.
- Cap thickness to accommodate bioturbation processes without compromising long-term effectiveness should correspond to the combined depth of the surficial and middepth zones, extending from the sediment/water interface to the maximum depth of biodiffusion.
- Total cap design thickness should exceed that allotted for accommodation of bioturbation processes alone.
- The best available knowledge on local bioturbators should supplement generic assumptions concerning bioturbation processes. Where site-specific data are lacking, conservative estimates of bioturbation depth should be made, particularly where the presence or absence of deep bioturbators is speculative. In most coastal or marine environments, bioturbation can be predicted to extend down to 20 to 60 cm, whereas in freshwater environments, comparable depths would be 20 to 40 cm.

- Bioturbation processes should be an integral component of models that predict contaminant fluxes through sediment layers. At a minimum, bioturbation should be treated as a two-layer system: an overlying continually mixed layer and an underlying biodiffusion layer.

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